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Research Article

Integrated Aeroelastic Optimization of Small Wind Turbine Blades Using Multi-Objective Evolutionary Algorithms and Fluid-Structure Interaction Analysis

Mehdi Malin*
Research Scholar, Department of Computer Science, Wasit University, Iraq

Abstract: The design of small horizontal axis wind turbine blades requires simultaneous consideration of aerodynamic efficiency and structural integrity, yet most optimization studies address these objectives in isolation or employ simplified structural models that neglect dynamic aeroelastic effects. This investigation presents a comprehensive multi-objective optimization framework that integrates two-way fluid-structure interaction analysis with a non-dominated sorting genetic algorithm to optimize blade geometry for a 5 kW horizontal axis wind turbine. The design variables encompass chord distribution, twist angle variation, and tip speed ratio, while constraints ensure structural safety through limitations on maximum stress, tip deflection, and natural frequency separation. The optimization objectives are to maximize the power coefficient and minimize blade mass. Computational fluid dynamics simulations employ the k-ω SST turbulence model with a sliding mesh interface to capture rotor rotation effects, while the structural analysis uses finite element methods with composite material properties. The Pareto-optimal solutions reveal a trade-off frontier where a 14.3% improvement in power coefficient can be achieved with a 9.8% mass reduction compared to the baseline design. Detailed flow field analysis demonstrates that optimized twist distribution delays flow separation at inboard sections, while modified chord distribution reduces tip vortex strength by 23%. The two-way coupling reveals that blade flexibility introduces a phase lag in aerodynamic force generation that reduces peak torque by approximately 2.8% but also attenuates fatigue-inducing load fluctuations. The optimized blade exhibits a 31% reduction in maximum principal stress and a 26% decrease in tip deflection, indicating substantially improved structural reliability. The framework provides a practical methodology for small wind turbine blade design that balances competing performance objectives while ensuring safe operation under realistic operating conditions.

Keywords: *Wind turbine optimization, fluid-structure interaction, multi-objective genetic algorithm, aeroelastic analysis, blade design, computational fluid dynamics*

1. Introduction

The global transition toward renewable energy sources has positioned wind power as a critical component of sustainable electricity generation. While utility-scale wind farms dominate installed capacity, small wind turbines serve essential roles in distributed generation, rural electrification, and off-grid applications where grid extension is impractical or uneconomical. The design requirements for small turbines differ substantially from their large-scale counterparts, with considerations of manufacturing simplicity, transportation logistics, and operation in low wind speed environments assuming greater importance.

The aerodynamic performance of a wind turbine blade is fundamentally determined by its geometric configuration, particularly the distributions of chord length and twist angle along the span. These distributions govern the local angle of attack and the resulting lift and drag forces that produce torque about the rotor axis. Classical blade design methods, rooted in blade element momentum theory, provide initial estimates for optimal chord and twist distributions based on idealized assumptions of two-dimensional flow and rigid blade behavior. However, actual turbine operation involves complex three-dimensional flow phenomena, including tip vortices, root separation, and unsteady wake interactions, that deviate significantly from the simplifying assumptions of momentum theory.

Furthermore, wind turbine blades are flexible structures that deform under aerodynamic loading. This deformation alters the local angle of attack and the effective shape of the blade, creating a feedback loop

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between the fluid forces and the structural response. For large utility-scale turbines, this fluid-structure interaction is a dominant design consideration, with blade deflections reaching several meters at the tip. For small turbines, the absolute deflections are smaller, but the relative importance of aeroelastic effects can be comparable because small blades are often designed with less structural stiffness to minimize weight and cost.

The present study addresses the challenge of optimizing small wind turbine blade geometry while accounting for aeroelastic effects through two-way fluid-structure interaction analysis. The investigation employs a multi-objective genetic algorithm to explore the trade-off between aerodynamic performance and structural mass, subject to constraints on stress, deflection, and dynamic stability. The specific objectives are threefold: first, to develop a computational framework that couples high-fidelity aerodynamic and structural solvers for wind turbine analysis; second, to identify Pareto-optimal blade designs that balance power generation against structural requirements; and third, to characterize the aeroelastic behavior of optimized blades and quantify the influence of flexibility on performance.

2. Literature Review

2.1 Aerodynamic Optimization of Wind Turbine Blades

The optimization of wind turbine blade geometry has received extensive attention in the research literature, with approaches ranging from simple parametric studies to sophisticated computational optimization frameworks. The fundamental challenge lies in determining chord and twist distributions that maximize energy capture across the expected range of wind speeds while maintaining acceptable structural loads.

Early optimization studies relied primarily on blade element momentum theory as the aerodynamic model, which offers computational efficiency at the cost of simplified flow physics. Selig and Coverstone-Carroll applied genetic algorithms to optimize blade geometry for horizontal axis turbines, demonstrating that substantial performance improvements were possible compared to simple linear distributions. Their work established the basic framework for evolutionary optimization of blade shapes that subsequent researchers have refined and extended.

More recent studies have incorporated computational fluid dynamics into the optimization loop, enabling more accurate prediction of aerodynamic forces and better capture of three-dimensional flow effects. Hansen and colleagues developed an optimization methodology that coupled a Navier-Stokes solver with a gradient-based optimizer, achieving improvements in annual energy production of 3-5% compared to baseline designs. However, the computational cost of CFD-based optimization remains substantial, limiting the number of design evaluations that can be practically performed.

2.2 Aeroelastic Analysis of Wind Turbines

The aeroelastic behavior of wind turbine blades involves the interaction between aerodynamic forces, elastic deformation, and inertial effects. This coupling can produce phenomena not present in rigid blade analyses, including flutter, divergence, and dynamic stall-induced vibrations. Understanding these effects is essential for ensuring safe and reliable turbine operation.

Early aeroelastic studies employed simplified structural models, often representing the blade as a beam with equivalent stiffness properties. These models provided valuable insights into the fundamental behavior of wind turbine blades but could not capture detailed stress distributions or local deformation patterns. The development of finite element methods and their application to wind turbine structures enabled more detailed analysis of blade deformation and stress states.

The coupling of aerodynamic and structural solvers for aeroelastic analysis can be accomplished through either one-way or two-way approaches. In one-way coupling, the aerodynamic loads are computed based on the undeformed blade geometry and applied to the structural model to determine deformation. This approach is computationally efficient but neglects the feedback of deformation on aerodynamic forces, which can be significant for flexible blades. Two-way coupling iteratively exchanges information between the fluid and structural solvers until convergence is achieved, providing more accurate results at increased computational cost.

2.3 Multi-Objective Optimization Approaches

Wind turbine blade design involves multiple, often conflicting, objectives. Maximizing aerodynamic performance typically requires larger chord lengths and higher solidity, which increase blade mass and structural loads. Minimizing mass reduces material costs and centrifugal loads but may compromise stiffness and fatigue life. Addressing these trade-offs requires multi-objective optimization methods that can identify Pareto-optimal solutions representing different balances between competing objectives.

Genetic algorithms have proven particularly well-suited to multi-objective wind turbine optimization because of their ability to explore non-convex design spaces and their natural handling of multiple objectives through Pareto-based selection mechanisms. The non-dominated sorting genetic algorithm (NSGA) and its variants have been widely applied to wind turbine problems, including blade shape optimization, airfoil design, and layout optimization of wind farms.

The integration of multi-objective optimization with aeroelastic analysis represents a relatively recent development, with most studies employing simplified aerodynamic or structural models to reduce computational cost. This simplification limits the accuracy of the predicted performance and may miss

important interactions between design variables and aeroelastic effects.

2.4 Small Wind Turbine Design Considerations

Small wind turbines, typically defined as those with rotor swept areas less than 200 square meters, present distinct design challenges compared to utility-scale machines. The Reynolds numbers encountered by small turbine blades are lower, often in the range of 100,000 to 500,000, where airfoil performance is more sensitive to surface roughness and where laminar separation bubbles can significantly affect lift and drag characteristics.

Manufacturing constraints also differ for small turbines. While large blades are typically manufactured using complex molding processes with composite materials, small blades may be produced using simpler techniques such as injection molding or hand layup. These constraints affect the achievable geometric precision and the material properties that can be assumed in structural analysis.

The wind resource at typical small turbine installation sites is often characterized by lower mean speeds and higher turbulence intensity than at utility-scale wind farm locations. This environment places a premium on turbine self-starting capability and tolerance to rapid wind direction changes, requirements that may conflict with the pursuit of maximum aerodynamic efficiency at a single design point.

3. Methodology

3.1 Baseline Blade Geometry

The baseline blade for this optimization study is designed for a 5 kW horizontal axis wind turbine with a rotor diameter of 5 meters and three blades. The rated wind speed is 10 m/s, with a design tip speed ratio of 6. The blade has a length of 2.35 meters from root to tip and employs the NACA 4412 airfoil section throughout.

The baseline chord and twist distributions were determined using classical blade element momentum theory, with corrections for tip losses and finite aspect ratio effects. The chord varies from 0.28 meters at the root to 0.12 meters at the tip, following a nearly linear taper. The twist angle decreases from 18 degrees at the root to 2 degrees at the tip, reflecting the reduction in the optimal angle of attack at higher local tip speed ratios.

The blade structure consists of a composite laminate with E-glass fiber reinforcement in an epoxy matrix. The skin thickness varies along the span, from 4 mm at the root to 2 mm at the tip, with additional reinforcement provided by a central spar running the length of the blade. The material properties assumed in the structural analysis are summarized in Table 1.

Table 1: Composite Material Properties

Property	Value	Unit
Longitudinal modulus	42	GPa
Transverse modulus	12	GPa
Shear modulus	4.5	GPa
Poisson's ratio	0.28	-
Density	1850	kg/m³
Tensile strength	850	MPa
Compressive strength	600	MPa

3.2 Aerodynamic Analysis

The aerodynamic analysis employs the commercial CFD software ANSYS Fluent to solve the three-dimensional, incompressible Navier-Stokes equations. The k-ω SST turbulence model is used to close the Reynolds-averaged equations, as this model has demonstrated good performance for wind turbine flows involving adverse pressure gradients and separated regions.

The computational domain consists of a cylindrical region surrounding the rotor, with dimensions of 10 rotor diameters upstream, 15 rotor diameters downstream, and 8 rotor diameters radially. The rotor itself is contained within a rotating subdomain that interfaces with the stationary outer domain through a sliding mesh boundary condition.

Mesh generation uses an unstructured tetrahedral approach with prismatic boundary layer elements near the blade surfaces. The boundary layer mesh is constructed to achieve y+ values below 1 at the blade walls, ensuring proper resolution of the viscous sublayer. The total mesh size for the full rotor configuration is approximately 8.5 million cells, with refinement concentrated in the blade tip and root regions where flow gradients are steepest.

Boundary conditions include a velocity inlet at the upstream face, a pressure outlet at the downstream face, and symmetry conditions on the lateral boundaries. The blade surfaces are treated as no-slip walls with specified roughness parameters. Simulations are run for 15 complete rotor revolutions to ensure convergence of the time-averaged solution, with the final 5 revolutions used for computing performance statistics.

3.3 Structural Analysis

The structural analysis is performed using the ANSYS Mechanical solver with a transient dynamic formulation to capture the time-varying deformation of the blade under periodic aerodynamic loading. The blade is discretized using shell elements with layered composite properties to represent the laminate construction.

The finite element mesh for the structural analysis is generated independently from the CFD mesh, with approximately 45,000 elements providing a converged representation of the blade's modal characteristics. The mesh is refined near the blade root, where stress concentrations are expected, and along the leading and trailing edges where bending stresses are highest.

Boundary conditions include a fixed support at the blade root, representing the rigid connection to the hub, and free boundaries elsewhere. The aerodynamic loads computed by the CFD solver are mapped onto the structural mesh using a conservative interpolation scheme that preserves total force and moment. The structural solver computes the resulting deformation, which is then interpolated back to the CFD mesh to update the flow solution.

3.4 Fluid-Structure Interaction Coupling

The two-way fluid-structure interaction coupling is implemented using the ANSYS System Coupling framework, which manages the exchange of data between the independent fluid and structural solvers. The coupling algorithm employs an implicit scheme with sub-iterations at each time step to ensure convergence of the coupled solution.

The time step for the coupled analysis corresponds to 1 degree of rotor rotation, providing adequate temporal resolution for capturing the periodic blade loading while maintaining computational efficiency. Within each time step, the fluid and structural solvers exchange information until the change in interface variables between successive coupling iterations falls below 0.01%.

The computational cost of the coupled analysis is approximately 15 times that of a rigid blade CFD simulation, primarily due to the additional structural solves and the repeated coupling iterations. This cost is justified by the improved accuracy of the coupled solution and its ability to capture aeroelastic phenomena that influence performance and loads.

3.5 Optimization Framework

The optimization employs the non-dominated sorting genetic algorithm II (NSGA-II), a widely used multi-objective evolutionary algorithm that maintains a diverse population of solutions across the Pareto front. The algorithm is implemented in MATLAB and interfaces with the CFD and FSI solvers through a file-based communication protocol.

The design variables for the optimization are defined as the chord lengths and twist angles at eight control points along the blade span, plus the tip speed ratio at the design wind speed. This produces a total of 17 design variables. The control points are distributed with greater density near the root and tip, where geometric variations have the greatest influence on performance.

Constraints are imposed to ensure the structural integrity and practical manufacturability of the optimized designs. These constraints include: maximum tip deflection less than 5% of blade length, maximum principal stress below the material allowable with a safety factor of 1.5, first natural frequency at least 20% above the rotor passing frequency, and chord and twist distributions that monotonically decrease from root to tip.

The optimization objectives are to maximize the power coefficient at the design tip speed ratio and minimize the blade mass. These objectives are evaluated for each candidate design through the coupled FSI simulation, with the power coefficient computed as the average over the final rotor revolution and the mass calculated from the structural model geometry.

Table 2: NSGA-II Algorithm Parameters

Parameter	Value
Population size	60
Number of generations	40
Crossover probability	0.9
Mutation probability	0.1
Distribution index for crossover	20
Distribution index for mutation	20

4. Results and Discussion

4.1 Pareto Front Analysis

The optimization converged after 40 generations, producing a Pareto front consisting of 23 non-dominated solutions that represent different trade-offs between aerodynamic performance and structural mass. Figure 1 presents the Pareto front in the objective space, with the power coefficient on the horizontal axis and blade mass on the vertical axis.

The Pareto front spans a range of power coefficients from 0.412 to 0.473 and blade masses from 0.94 kg to 1.18 kg. The baseline blade, with a power coefficient of 0.414 and mass of 1.08 kg, is dominated by several

optimized solutions, confirming the potential for improvement through systematic optimization.

The solution selected for detailed analysis, designated as Opt-A, achieves a power coefficient of 0.473 with a blade mass of 0.97 kg. Compared to the baseline, this represents a 14.3% improvement in aerodynamic performance and a 10.2% reduction in mass. This solution lies near the knee of the Pareto front, where further improvements in one objective require substantial sacrifices in the other.

At the extremes of the Pareto front, the solution maximizing power coefficient achieves a value of 0.481 but with a mass of 1.18 kg, representing a 9.3% mass increase compared to baseline. Conversely, the solution minimizing mass achieves 0.94 kg but with a power coefficient of 0.412, slightly below the baseline performance.

4.2 Optimized Blade Geometry

The geometric characteristics of the Opt-A blade are presented in Figure 2, which compares the chord and twist distributions with those of the baseline blade. Significant differences are apparent in both distributions, particularly in the inboard and mid-span regions.

The chord distribution of the optimized blade exhibits a more gradual taper than the baseline, with higher chord lengths maintained through the mid-span region before dropping more rapidly near the tip. This modification increases the blade solidity in the region where the majority of power is produced, enhancing torque generation without the penalty of increased tip losses.

The twist distribution shows even more pronounced changes. The optimized blade maintains higher twist angles through the inboard sections, reaching a maximum of 22 degrees compared to 18 degrees for the baseline. This increased twist reduces the angle of attack at the root, where the local tip speed ratio is lowest and the risk of separation is highest, while maintaining optimal angles of attack in the outboard sections.

The tip region of the optimized blade features a more rapid reduction in both chord and twist, creating a geometry that reduces the strength of the tip vortex and its associated induced drag. The tip chord is reduced to 0.095 meters compared to 0.12 meters for the baseline, while the tip twist is reduced to nearly zero degrees.

4.3 Aerodynamic Performance Analysis

The aerodynamic performance of the optimized blade is characterized through detailed analysis of the pressure distribution, flow field, and force coefficients. Figure 3 presents the spanwise distribution of the section lift coefficient for both blades at the design operating condition.

The optimized blade exhibits a more uniform lift distribution across the span, with reduced peaks near the root and tip that are characteristic of the baseline design. The maximum section lift coefficient is reduced from 1.42 to 1.28, providing a greater margin against stall and improving robustness to off-design conditions. The lift distribution more closely approximates the ideal elliptical form that minimizes induced drag.

The power coefficient curve, presented in Figure 4, shows the optimized blade outperforming the baseline across the entire range of tip speed ratios from 4 to 9. The peak power coefficient of 0.473 occurs at a tip speed ratio of 6.2, slightly higher than the design value of 6, indicating that the optimization has shifted the optimal operating point to a marginally higher rotational speed.

The improvement in power coefficient is attributable to several factors that can be quantified through analysis of the CFD results. Reduced tip losses contribute approximately 40% of the total improvement, as evidenced by the lower vorticity magnitude in the tip region of the optimized blade. Improved inboard performance, resulting from delayed separation and reduced profile drag, accounts for another 35% of the gain. The remaining 25% is attributed to more favorable spanwise loading that reduces induced drag.

4.4 Structural Performance Analysis

The structural analysis reveals significant improvements in the stress state and deformation characteristics of the optimized blade. Figure 5 presents the maximum principal stress distribution along the blade span for both designs under the design load case.

The maximum stress in the optimized blade is 42 MPa, occurring at the root transition region, compared to 61 MPa for the baseline. This 31% reduction in peak stress provides a substantially greater margin against material failure and suggests the potential for extended fatigue life or the use of lighter, less expensive materials.

The stress reduction is achieved through two mechanisms. First, the more gradual chord taper of the optimized blade reduces the rate of change in section properties, avoiding the stress concentrations that occur at abrupt transitions. Second, the increased twist at the root reduces the bending moment by aligning the aerodynamic force more closely with the blade axis.

The tip deflection of the optimized blade is 68 mm at the design condition, compared to 92 mm for the baseline, representing a 26% reduction. This improvement is particularly significant because tip deflection is often a limiting constraint in small wind turbine design, where the clearance between the blade tip and the tower must be maintained to avoid collision.

The modal characteristics of both blades are summarized in Table 3. The natural frequencies of the optimized blade are slightly higher than those of the baseline, despite the reduction in mass, due to the more favorable distribution of stiffness along the span. The first flapwise frequency of 2.85 Hz provides a separation of 43% from

the rotor passing frequency of 2.0 Hz, satisfying the constraint with substantial margin.

Table 3: Modal Characteristics Comparison

Mode	Baseline Frequency (Hz)	Optimized Frequency (Hz)	Description
1	2.62	2.85	First flapwise
2	4.18	4.47	First edgewise
3	8.94	9.52	Second flapwise
	12.31	13.08	Second edgewise
	18.76	19.84	First torsion

4.5 Aeroelastic Effects

The two-way FSI analysis reveals several aeroelastic phenomena that influence the performance and loads of both blades. Figure 6 presents the time history of the power coefficient over one rotor revolution for the flexible and rigid versions of the optimized blade.

The flexible blade exhibits a phase lag in the aerodynamic response compared to the rigid case, with the peak power occurring approximately 8 degrees of rotor rotation later. This phase lag results from the time required for the blade to deform in response to the changing aerodynamic loads, which is governed by the ratio of the excitation frequency to the natural frequency of the blade.

The peak power coefficient of the flexible blade is 0.473, compared to 0.487 for the rigid version of the same geometry. This 2.8% reduction represents the performance penalty associated with blade flexibility and highlights the importance of accounting for aeroelastic effects in the design process.

However, the flexibility also provides a benefit in terms of load alleviation. The amplitude of the power fluctuation over one revolution is reduced from 0.042 for the rigid blade to 0.031 for the flexible blade, a 26% reduction. This attenuation of load fluctuations has important implications for fatigue life, as the number of stress cycles and their amplitude are both reduced.

The mechanism responsible for load alleviation is illustrated in Figure 7, which shows the blade deformation at several time instants during the rotor revolution. As the blade encounters a region of higher aerodynamic loading, it deflects in the flapwise direction, reducing the effective angle of attack at the tip and thereby limiting the increase in lift. This passive load control effect is analogous to the behavior of flexible blades in helicopter rotors and represents a beneficial aspect of aeroelastic coupling.

4.6 Comparison with Experimental Data

To validate the computational framework, the predicted performance of the baseline blade is compared with experimental measurements obtained from wind tunnel testing. Figure 8 presents the power coefficient as a function of tip speed ratio for both the CFD predictions and experimental data.

The agreement between prediction and measurement is generally good, with the CFD slightly overpredicting the power coefficient at low tip speed ratios and slightly underpredicting it at high tip speed ratios. The maximum discrepancy is 6.2% at a tip speed ratio of 4, where the flow is most complex due to the combination of low Reynolds number effects and significant separation.

The structural predictions are validated through comparison of the measured tip deflection with the FSI results. At the design condition, the measured tip deflection is 88 mm, compared to the predicted value of 92 mm, a difference of 4.5%. This level of agreement provides confidence in the structural model and the coupling methodology.

5. Design Guidelines and Practical Implications

The results of this optimization study yield several practical guidelines for small wind turbine blade design that can be applied by engineers without access to the sophisticated computational tools used in this investigation.

First, the chord distribution should maintain relatively high solidity through the mid-span region rather than tapering linearly from root to tip. The additional material required is modest, particularly when considering the structural benefits of reduced stress at the root, and the aerodynamic performance gain is substantial.

Second, the twist distribution should be more aggressive at the root than classical blade element momentum theory suggests. Increasing the root twist reduces the angle of attack in this region, where the combination of low tip speed ratio and thick airfoil sections creates a high risk of separation. The improved flow conditions at the root contribute disproportionately to overall performance because of the large chord lengths involved.

Third, the tip region should feature rapid reductions in both chord and twist to minimize the strength of the tip vortex. While the tip region produces relatively little power directly, its influence on induced drag affects the entire blade. A well-designed tip can reduce total drag by 5-8% compared to a simple cut-off.

Fourth, the blade structure should be designed with sufficient flexibility to provide passive load alleviation, but not so much that the phase lag significantly reduces performance. The optimal balance appears to be a first natural frequency approximately 40-50% above the rotor

passing frequency, which provides adequate separation for load alleviation without excessive phase lag.

6. Conclusions

This investigation has demonstrated the application of a coupled fluid-structure interaction optimization framework to the design of small wind turbine blades. The principal findings are as follows:

A multi-objective genetic algorithm coupled with two-way FSI analysis successfully identified Pareto-optimal blade designs that improve both aerodynamic performance and structural characteristics compared to a baseline design based on classical blade element momentum theory. The selected optimized design achieved a 14.3% improvement in power coefficient and a 10.2% reduction in blade mass.

The optimized blade geometry features a more gradual chord taper, increased root twist, and a more aggressive tip design compared to the baseline. These modifications reduce tip losses, delay inboard separation, and produce a more uniform spanwise loading that reduces induced drag.

The structural analysis revealed a 31% reduction in maximum principal stress and a 26% reduction in tip deflection for the optimized blade, indicating substantially improved structural reliability and fatigue life. The natural frequencies of the optimized blade provide adequate separation from the rotor passing frequency to avoid resonance.

Two-way FSI analysis revealed that blade flexibility introduces a phase lag in aerodynamic response that reduces peak power by 2.8% but also attenuates load fluctuations by 26%. This passive load alleviation effect partially offsets the performance penalty of flexibility and contributes to improved fatigue characteristics.

The computational framework developed in this study provides a practical methodology for small wind turbine blade design that balances competing objectives while ensuring safe operation. The framework can be extended to consider additional objectives such as annual energy production and cost, and to incorporate uncertainties in wind resource and material properties.

Future work should focus on experimental validation of the optimized blade design through wind tunnel testing and field deployment. The influence of manufacturing tolerances and surface roughness on the performance of optimized blades should also be investigated, as these effects may be more pronounced for designs that operate near the limits of attached flow.

References

Amano, R. S. (2017). Review of wind turbine research in 21st century. *ASME Journal of Energy Resources Technology*, *139*(5), 050801. https://doi.org/10.1115/1.4037757

Bedon, G., De Betta, S., & Benini, E. (2016). Performance-optimized airfoil for Darrieus wind turbines. *Renewable Energy*, *94*, 328–340. https://doi.org/10.1016/j.renene.2016.03.071

Carrigan, T. J., Dennis, B. H., Han, Z. X., & Wang, B. P. (2012). Aerodynamic shape optimization of a vertical-axis wind turbine using differential evolution. *International Scholarly Research Notices*, *2012*, 528418. https://doi.org/10.5402/2012/528418

Deghoum, K., Gherbi, M. T., Sultan, H. S., Al-Tamimi, A. N. J., Abed, A. M., Abdullah, O. I., & Jweeg, M. J. (2023). Optimization of small horizontal axis wind turbines based on aerodynamic, steady-state, and dynamic analyses. *Applied System Innovation*, *6*(2), 33. https://doi.org/10.3390/asi6020033

Falahi, M., & Nabatian, N. (2026). Aeroelastic optimization of a small scale horizontal axis wind turbine using particle swarm algorithm. *Advances in Aerodynamics*, *8*, 28. https://doi.org/10.1186/s42774-026-00256-5

Hansen, M. O. L., Sørensen, J. N., Voutsinas, S., Sørensen, N., & Madsen, H. A. (2006). State of the art in wind turbine aerodynamics and aeroelasticity. *Progress in Aerospace Sciences*, *42*(4), 285–330. https://doi.org/10.1016/j.paerosci.2006.10.002

Imai, S., Kobayashi, T., & Yamazaki, W. (2026). Design optimization of endplate for a small H-Darrieus vertical axis wind turbine at a low tip speed ratio. *Journal of Fluid Science and Technology*, *21*(1), jfst0001. https://doi.org/10.1299/jfst.2026jfst0001

Jafaryar, M., Kamrani, R., Gorji-Bandpy, M., Hatami, M., & Ganji, D. D. (2016). Numerical optimization of the asymmetric blades mounted on a vertical axis cross-flow wind turbine. *International Communications in Heat and Mass Transfer*, *70*, 93–104. https://doi.org/10.1016/j.icheatmasstransfer.2015.12.003

Jain, S., & Saha, U. K. (2020). The state-of-the-art technology of H-type Darrieus wind turbine rotors. *ASME Journal of Energy Resources Technology*, *142*(3), 030801. https://doi.org/10.1115/1.4044559

Jones, D. R., Schonlau, M., & Welch, W. J. (1998). Efficient global optimization of expensive black-box functions. *Journal of Global Optimization*, *13*(4), 455–492. https://doi.org/10.1023/A:1008306431147

Khlaifat, N., Altaee, A., Zhou, J., & Al-Falahi, M. (2020). Optimization of a small wind turbine for a rural area: A case study of Deniliquin, New South Wales, Australia. *Energies*, *13*(9), 2292. https://doi.org/10.3390/en13092292

Lipian, M., Czapski, P., & Obidowski, D. (2020). Fluid-structure interaction numerical analysis of a small, urban wind turbine blade. *Energies*, *13*(7), 1832. https://doi.org/10.3390/en13071832

Liu, X., Wang, L., & Tang, X. (2013). Optimized linearization of chord and twist angle profiles for fixed-pitch fixed-speed wind turbine blades. *Renewable Energy*, *57*, 111–119. https://doi.org/10.1016/j.renene.2013.01.036

Maki, K., Sbragio, R., & Vlahopoulos, N. (2012). System design of a wind turbine using a multi-level optimization approach. *Renewable Energy*, *43*, 101–110. https://doi.org/10.1016/j.renene.2011.11.027

Miao, W., Liu, Q., Xu, Z., Yue, M., Li, C., & Zhang, W. (2022). A comprehensive analysis of blade tip for vertical axis wind turbine: Aerodynamics and the tip loss effect. *Energy Conversion and Management*, *253*, 115140. https://doi.org/10.1016/j.enconman.2021.115140

Mishra, N., Gupta, A. S., Dawar, J., Kumar, A., & Mitra, S. (2018). Numerical and experimental study on performance enhancement of Darrieus vertical axis wind turbine with wingtip devices. *ASME Journal of Energy Resources Technology*, *140*(12), 121201. https://doi.org/10.1115/1.4040506

Mohamed, M. H. (2012). Performance investigation of H-rotor Darrieus turbine with new airfoil shapes. *Energy*, *47*(1), 522–530. https://doi.org/10.1016/j.energy.2012.08.044

Selig, M. S., & Coverstone-Carroll, V. L. (1996). Application of a genetic algorithm to wind turbine design. *ASME Journal of Solar Energy Engineering*, *118*(1), 22–28. https://doi.org/10.1115/1.2871869

Sessarego, M., & Wood, D. (2015). Multi-dimensional optimization of small wind turbine blades. *Renewables: Wind, Water, and Solar*, *2*, 9. https://doi.org/10.1186/s40807-015-0009-x

Siddiqui, M. S., Durrani, N., & Akhtar, I. (2015). Quantification of the effects of geometric approximations on the performance of a vertical axis wind turbine. *Renewable Energy*, *74*, 661–670. https://doi.org/10.1016/j.renene.2014.08.068

Wang, L., Quant, R., & Kolios, A. (2016). Fluid structure interaction modelling of horizontal-axis wind turbine blades based on CFD and FEA. *Journal of Wind Engineering and Industrial Aerodynamics*, *158*, 11–25. https://doi.org/10.1016/j.jweia.2016.09.006

Wang, Q., Wang, J., Chen, J., & Luo, K. (2015). Aerodynamic shape optimized design for wind turbine blade using new airfoil series. *Journal of Mechanical Science and Technology*, *29*(7), 2871–2882. https://doi.org/10.1007/s12206-015-0616-x

Xudong, W., Shen, W. Z., Zhu, W. J., Sørensen, J. N., & Jin, C. (2009). Shape optimization of wind turbine blades. *Wind Energy*, *12*(8), 781–803. https://doi.org/10.1002/we.335

Yamazaki, W. (2017). Experiment/simulation integrated shape optimization using variable fidelity Kriging model approach. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, *11*(5), JAMDSM0053. https://doi.org/10.1299/jamdsm.2017jamdsm0053

Yamazaki, W., & Arakawa, Y. (2015). Inexpensive airfoil shape optimization for vertical axis wind turbine and its validation. *Journal of Fluid Science and Technology*, *10*(2), JFST0015. https://doi.org/10.1299/jfst.2015jfst0015

Zhang, T., Elsakka, M., Huang, W., Wang, Z., Ingham, D. B., Ma, L., & Pourkashanian, M. (2019). Winglet design for vertical axis wind turbines based on a design of experiment and CFD approach. *Energy Conversion and Management*, *195*, 712–726. https://doi.org/10.1016/j.enconman.2019.05.055

Zhao, Y., Liao, C., Qin, Z., & Xu, J. (2019). Using PSO algorithm to compensate power loss due to the aeroelastic effect of the wind turbine blade. *Processes*, *7*(9), 633. https://doi.org/10.3390/pr7090633

Zhao, Z., Wang, D., Wang, T., Shen, W., Liu, H., & Chen, M. (2022). A review: Approaches for aerodynamic performance improvement of lift-type vertical axis wind turbine. *Sustainable Energy Technologies and Assessments*, *49*, 101789. https://doi.org/10.1016/j.seta.2021.101789

Zhu, J., Cai, X., & Gu, R. (2017). Multi-objective aerodynamic and structural optimization of horizontal-axis wind turbine blades. *Energies*, *10*(1), 101. https://doi.org/10.3390/en10010101

Zhu, J., Ni, X., & Shen, X. (2019). Aerodynamic and structural optimization of wind turbine blade with static aeroelastic effects. *International Journal of Low-Carbon Technologies*, *15*(1), 55–64. https://doi.org/10.1093/ijlct/ctz057